Determining Unknown Boundary Conditions in Fluid-Thermal Systems Using the Dynamic Data Driven Application Systems Methodology

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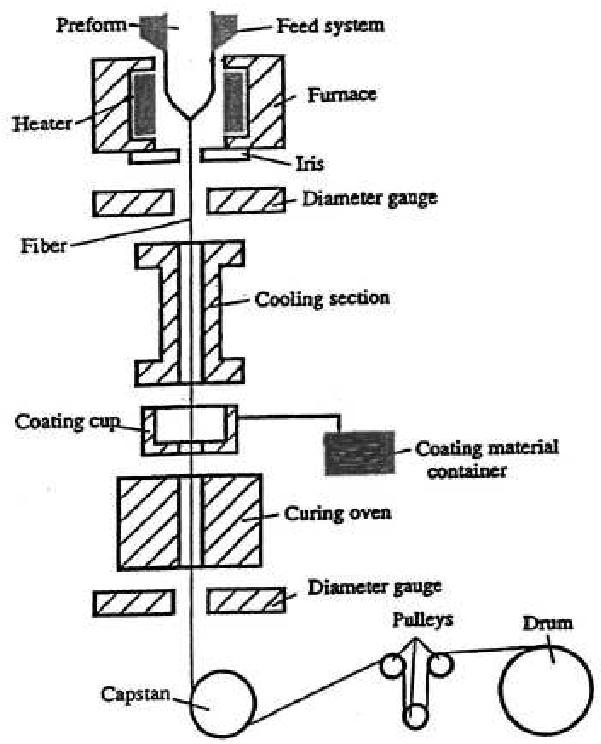
Outline

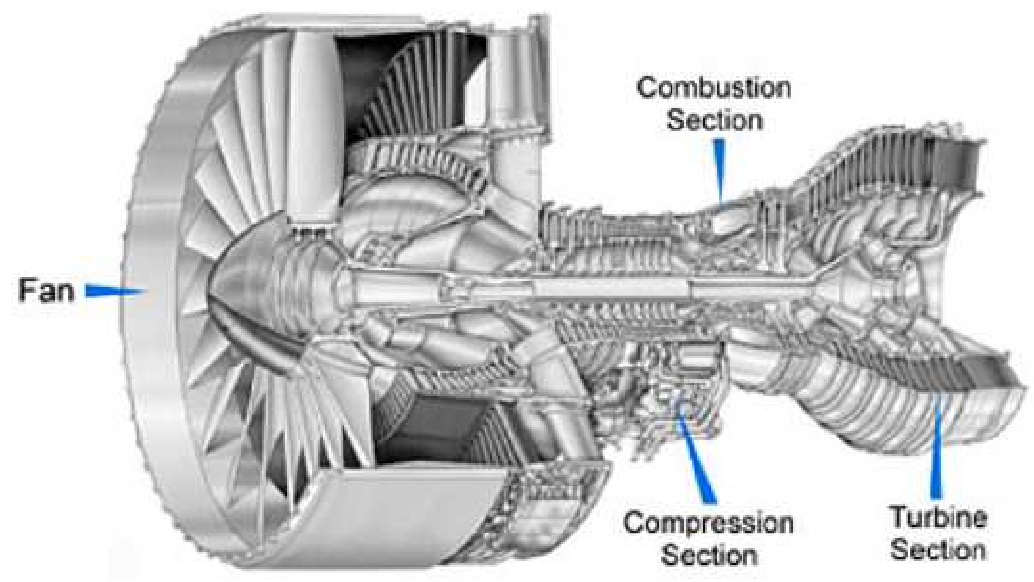
- Introduction
- Problem Definition
- Dynamic Data Driven Applications System Methodology
- Results
- Conclusions

Introduction

- In many engineering applications involving fluid-thermal systems, detailed quantitative infomation on the flow, temperature and species concentration is needed for system optimization



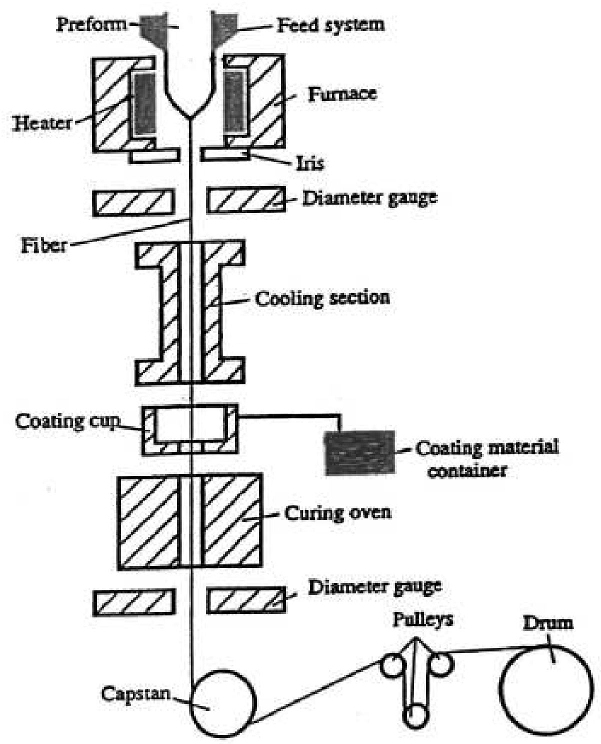
Optical fibre furnace



Turbofan engine

- Numerical simulation can obtain the desired information and thus optimize the system

  However, this approach requires well-defined boundary and operating conditions which may not be completely known due to limited access for experimental measurements



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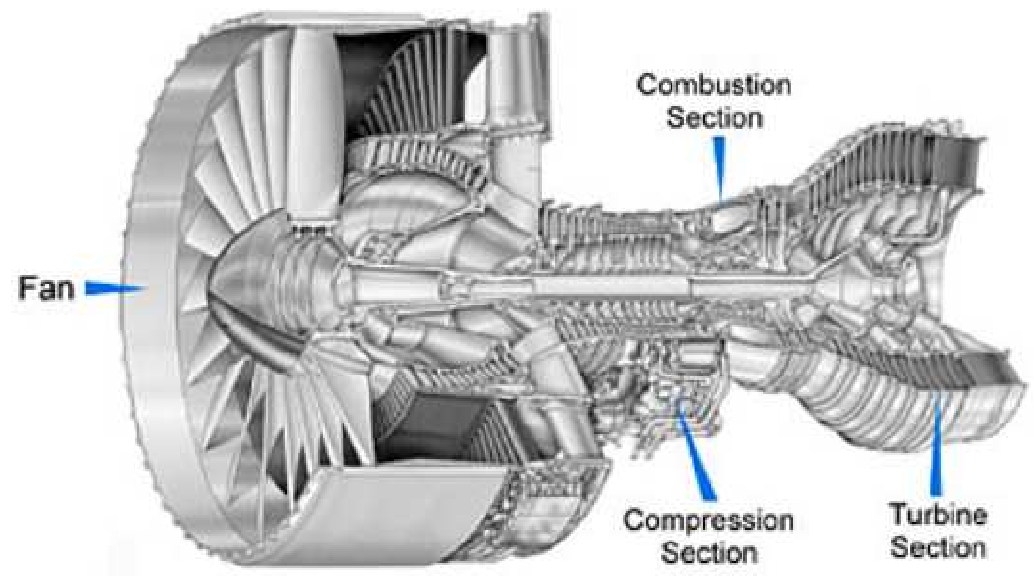
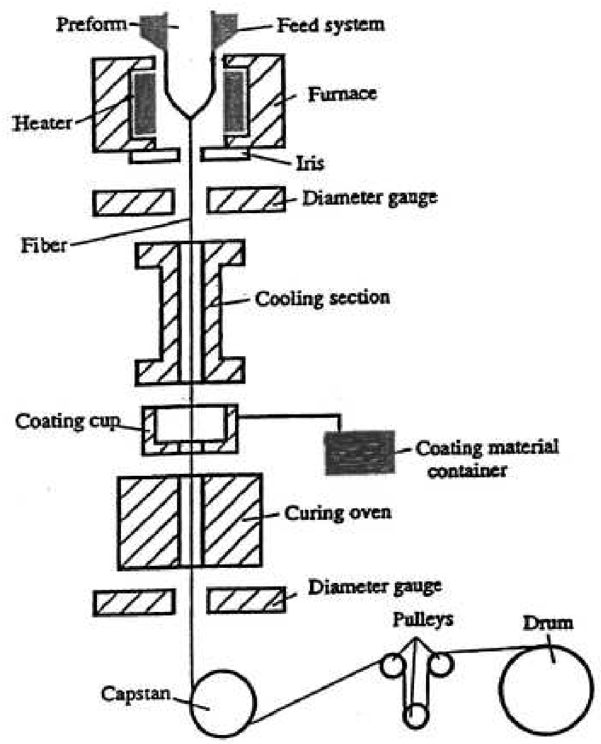


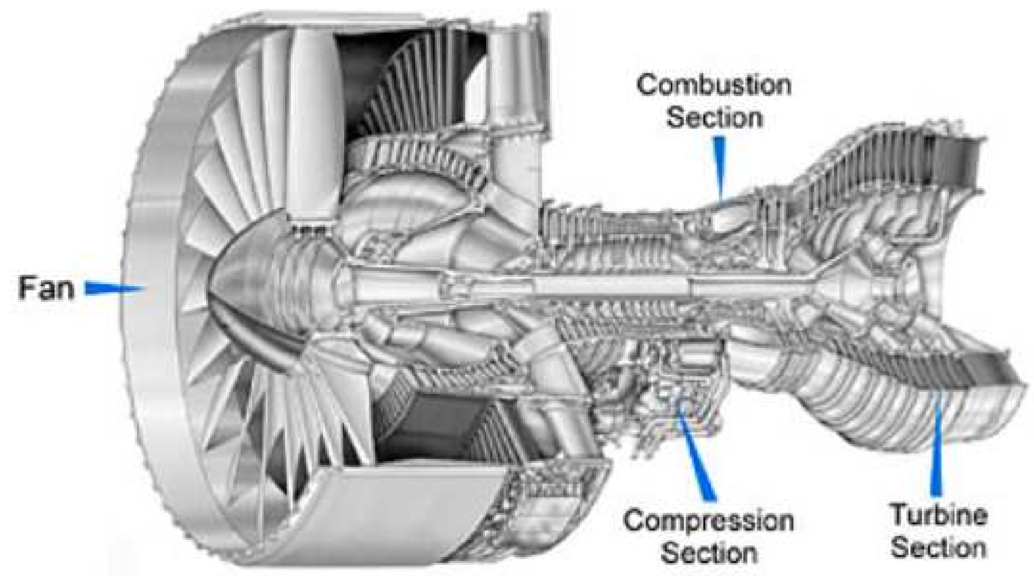
Turbofan engine

Introduction

- The objective of our research is to develop a Dynamic Data Driven Applications System approach that synergizes experiment and simulation to determine the boundary and operating conditions, thereby achieving a full simulation capability



Optical fibre furnace



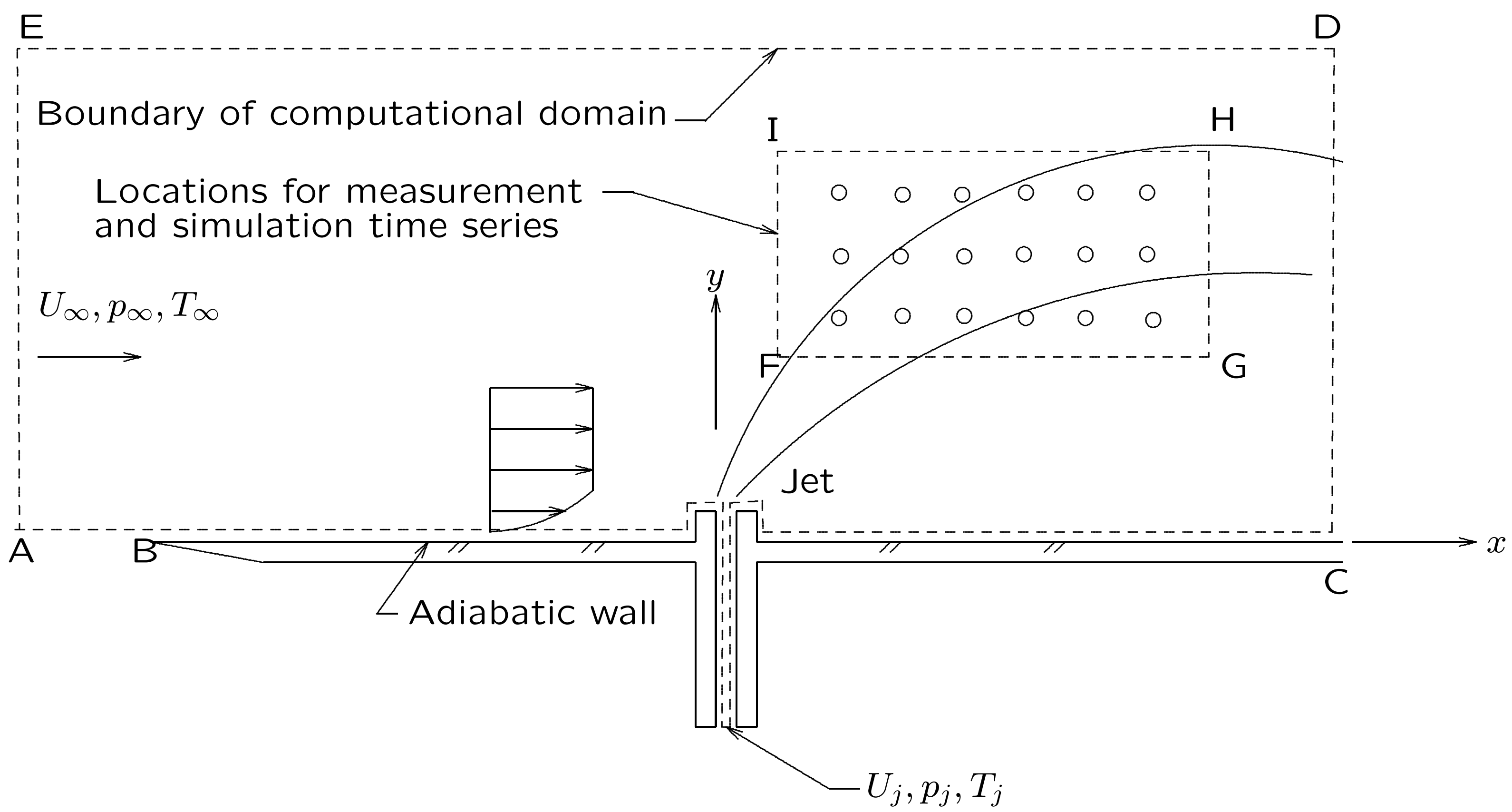
Turbofan engine

Problem Definition

Jet in Crossflow

- Heated wall jet in crossflow

  The objective is to determine the jet inflow conditions (U_j, T_j) using a Dynamic Data Driven Applications Systems method that synergizes experiment and simulation



Parameters

Item	*Known*	*Unknown*
U_∞	$\surd$	
T_∞	$\surd$	
p_∞	$\surd$	
U_j		$\surd$
T_j		$\surd$
p_j	$\surd$	

Problem Definition

Jet in Crossflow

- Experiment

  Rutgers Low Speed Wind Tunnel

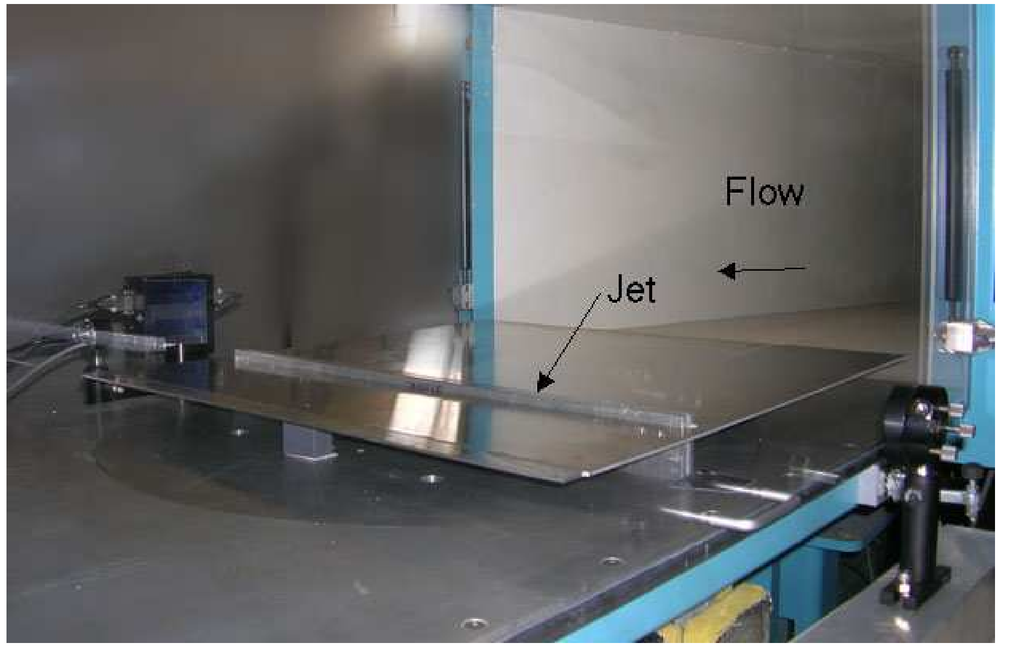
  Non-intrusive laser diode measurement

  Measure absorbance *vs* time at fixed (x, y)

  Static temperature T *vs* time from absorbance

  Limited region for absorbance measurement

  Each (x, y) measurement requires $\approx$ 1 hr



Experimental configuration

Problem Definition

Jet in Crossflow

- Laser diode absorbance

  Instantaneous absorbance

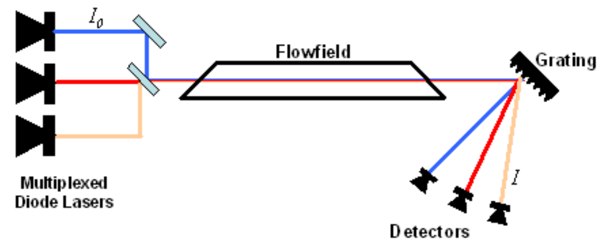
$$\mathcal{A}(x,y) = \frac{(I_o - I(x,y,t))}{I_o}$$

  where I_o is incident intensity at (x,y,z_1) and $I(x,y,t)$ is transmitted intensity at (x,y,z_2)

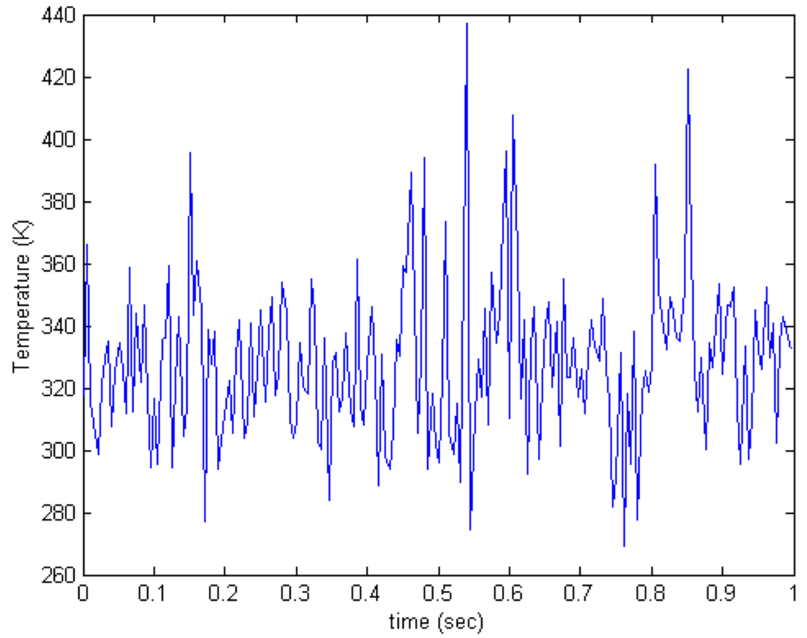
  Absorbance per cm of the ${}^{Q}R_2(6)$ line of the oxygen transition $b_1\Sigma_g^+\nu' = 0 \leftarrow X^3\Sigma_g^-\nu'' = 0$ at 761.139 nm is

$$\frac{d\mathcal{A}}{dz} = 0.083\,T^{-1} - 2.26 \cdot 10^{-5}$$

  where $T(x,y,z,t)$ is the static temperature in K



Laser diode arrangement



Typical T *vs* time

Problem Definition

Jet in Crossflow

- Simulation

  Laminar Navier-Stokes equations

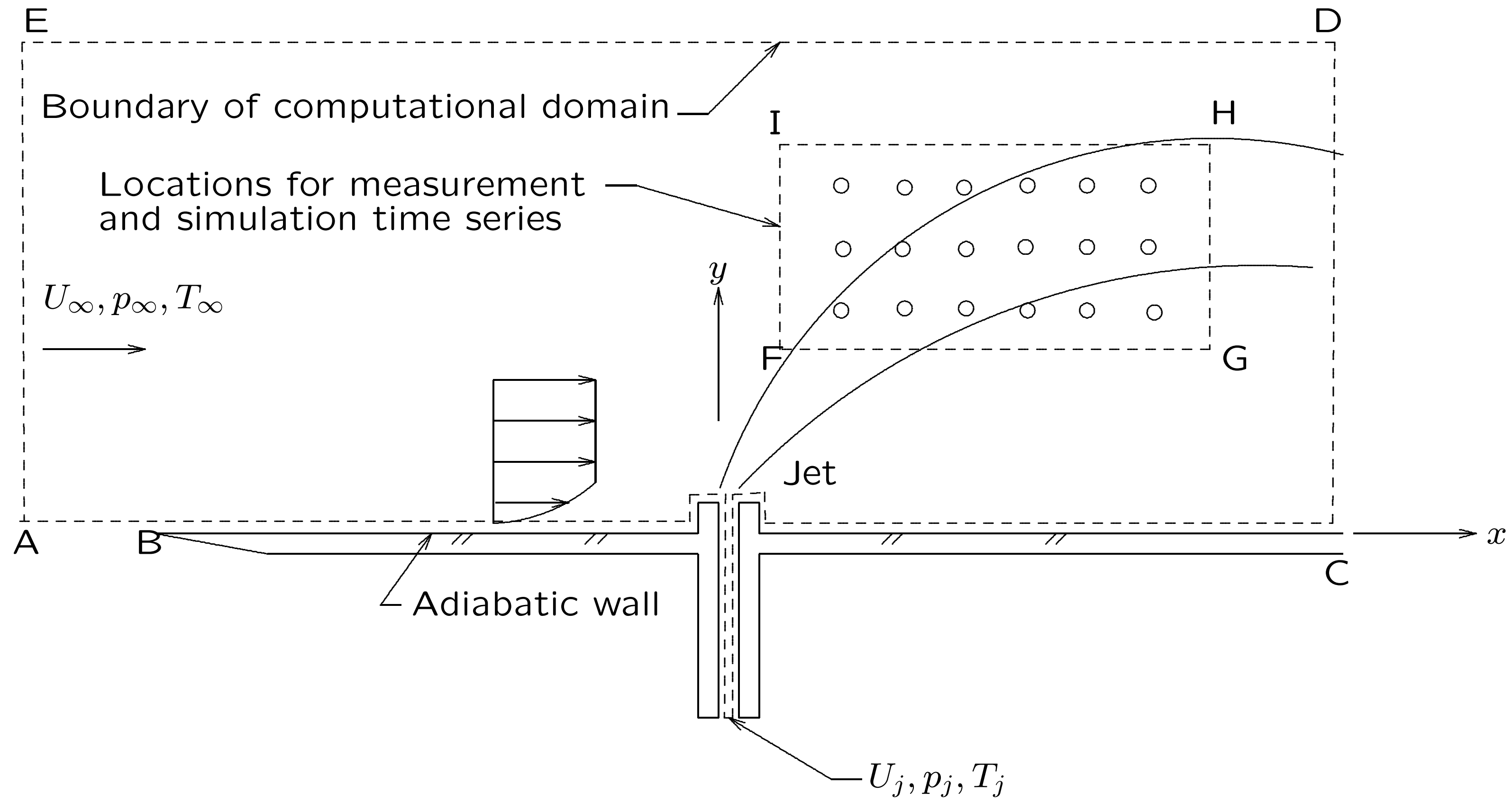
  Incompressible, ideal gas

  Unsteady, time-dependent

  Sutherland viscosity law

  Fluent©

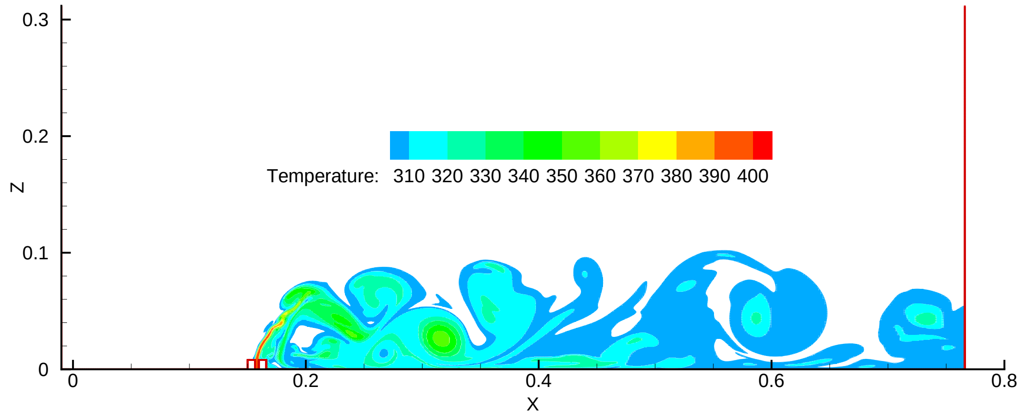
  Parallel (8 processors)



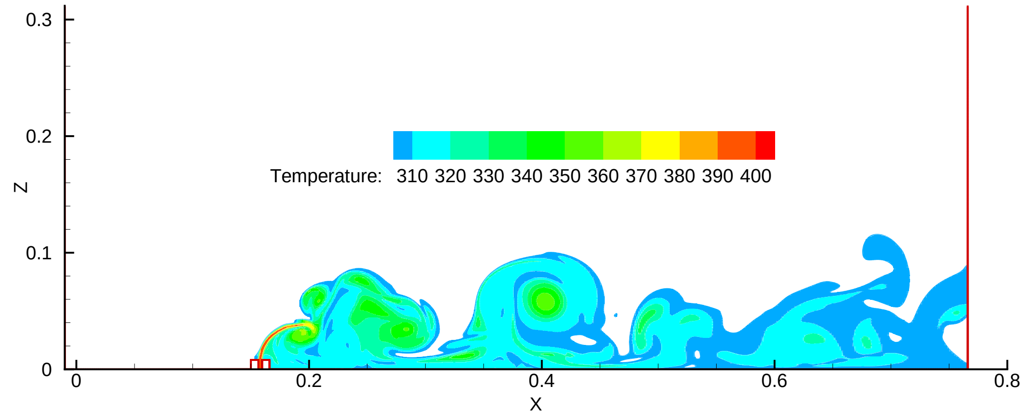
Problem Definition

Jet in Crossflow

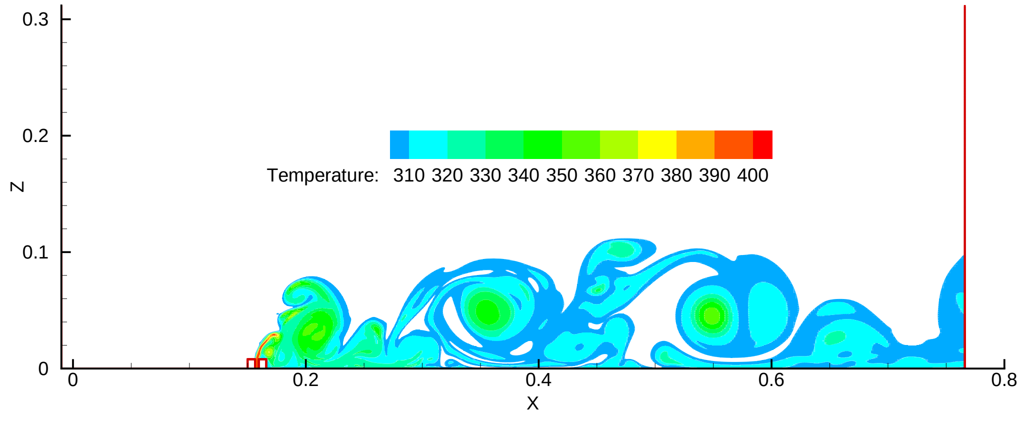
- Flow Structure



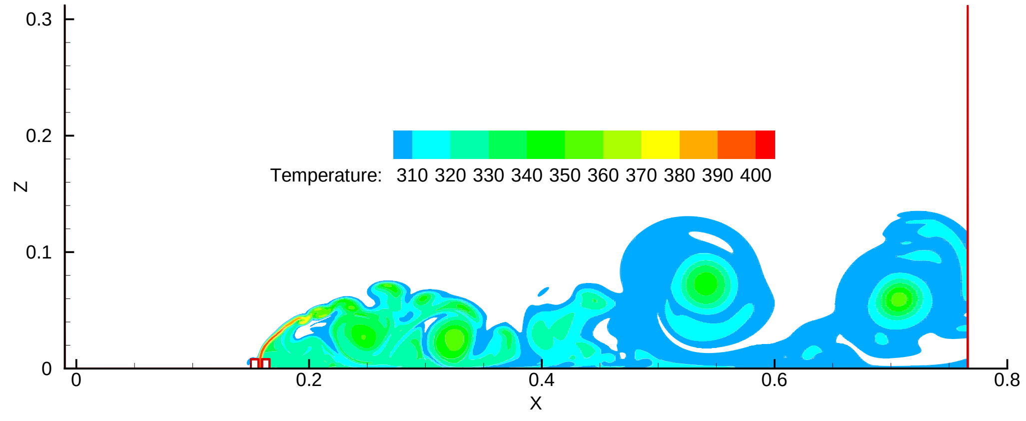
$t = 0$



$t = 40$ ms



$t = 80$ ms



$t = 120$ ms

Problem Definition

Jet in Crossflow

- Assumptions

  Large set S_s of discrete data locations defined ($\leq$ no. of grid cells in simulation)

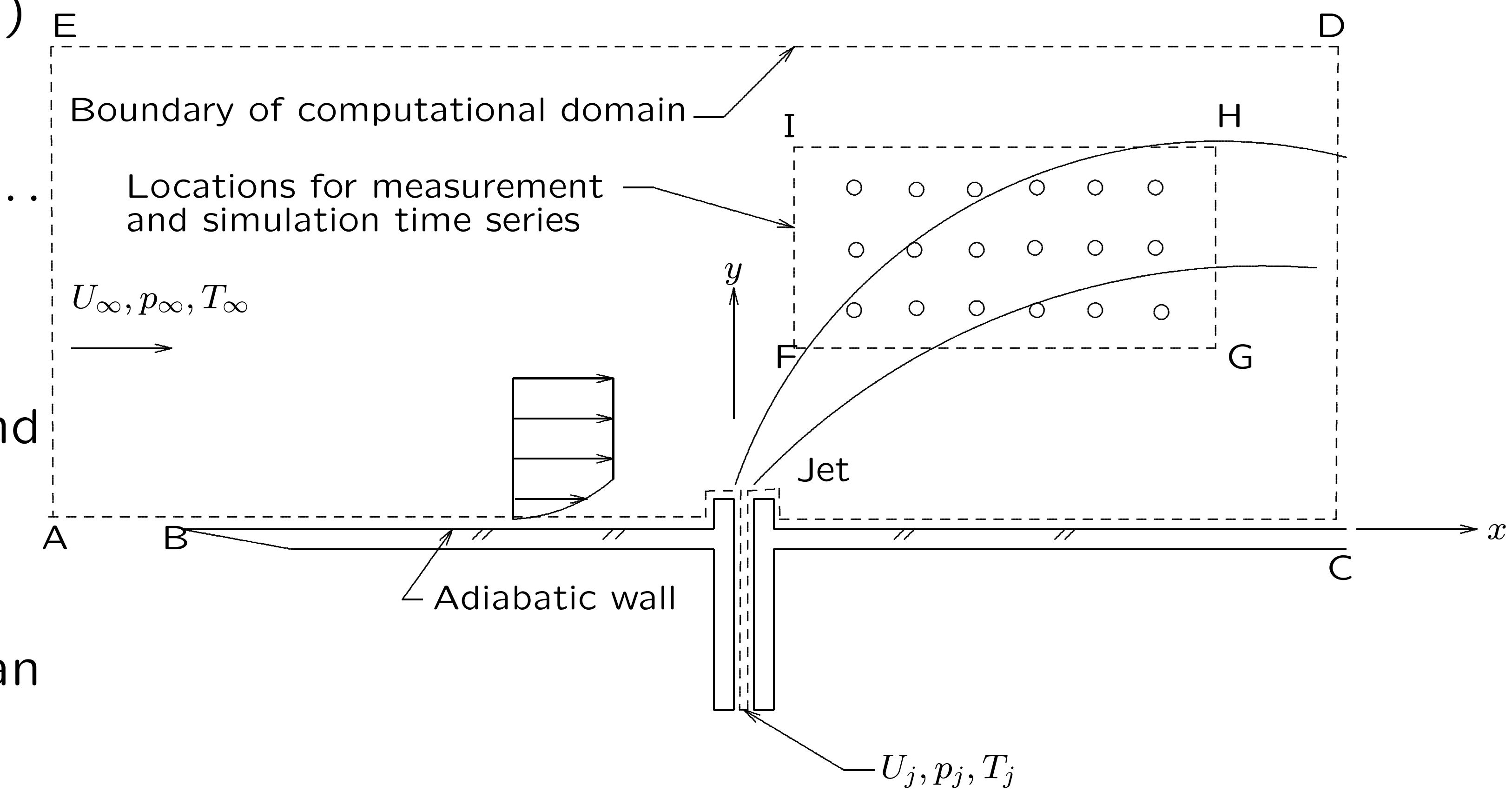
  For each experiment, time series data obtained for small subset $S_e^k, k = 1, 2, \ldots$ of locations

  For each simulation, time series data obtained for entire set S_s for each U_j and T_j

- The quantity for comparison between experiment and simulation is the mean temperature $T_m(x, y)$

- Problem

  Develop and apply a DDDAS Methodology for determining U_j and T_j



Response Surface Models

- Energy equation decouples from the mass and momentum equations
- Instantaneous temperature behaves as passive scalar and thus must scale as

$$T(x, y, t) - T_\infty = (T_j - T_\infty) f(x, y, t; U_j, U_\infty)$$

- Response Surface Model

$$T_m(x,y) - T_\infty = \left(T_j - T_\infty\right)\left[\beta_o(x,y) + \beta_1(x,y)\left(\frac{U_j}{U_\infty}\right) + \beta_2(x,y)\left(\frac{U_j}{U_\infty}\right)^2\right]$$

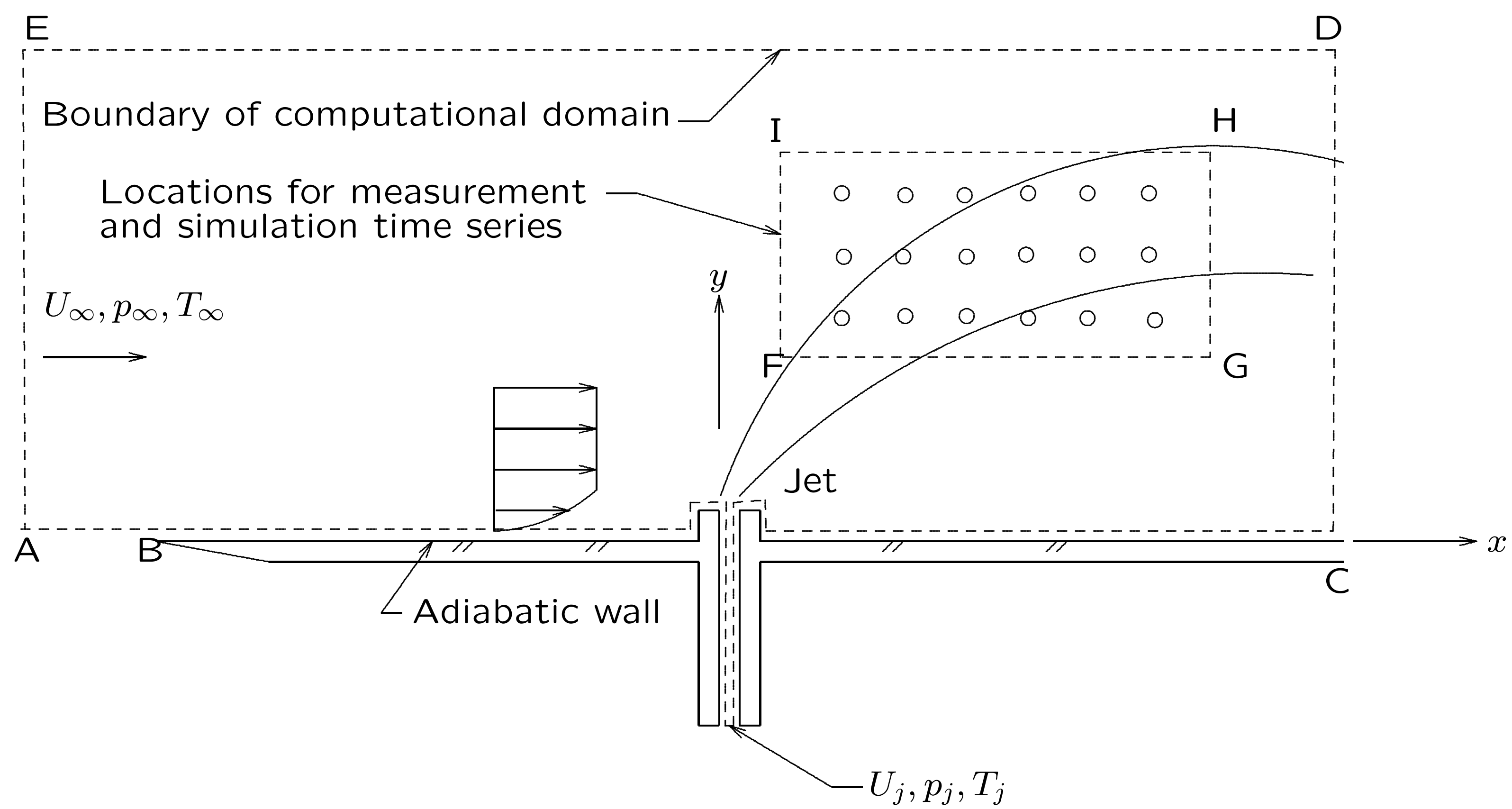
- The coefficients $\beta_i(x, y)$ are obtained from simulations performed for a fixed value $T_j - T_\infty$ (selected from the range indicated in Table) and a set of U_j

Flow Conditions

Parameter	*Value*
U_∞ (m/s)	4.0
T_∞ (K)	290.
p_∞ (kPa)	101.8
U_j (m/s)	4.0 to 8.0
T_j (K)	350 to 450
p_j (kPa)	101.8

Dynamic Data Driven Applications System Methodology

1. Select monitor locations S_s for simulations
2. Generate Response Surface Models based on simulations for fixed ΔT_j^i
3. Select monitor locations S_e^k for experiments
4. Estimate experimental values for $T_j - T_\infty$ and U_j using Response Surface Models and experimental data at monitor locations
5. Repeat at Step No. 2 if estimated $T_j - T_\infty$ is significantly different than used to generate Response Surface Models; otherwise, determine new measurement locations S_e^{k+1}
6. Repeat until converged



No.	x	y	*No.*	x	y	*No.*	x	y
1	1.2	2.0	7	1.2	3.0	13	1.2	4.0
2	3.2	2.0	8	3.2	3.0	14	3.2	4.0
3	5.2	2.0	9	5.2	3.0	15	5.2	4.0
4	7.2	2.0	10	7.2	3.0	16	7.2	4.0
5	9.2	2.0	11	9.2	3.0	17	9.2	4.0
6	11.2	2.0	12	11.2	3.0	18	11.2	4.0

Distances in cm from jet center

Dynamic Data Driven Applications System Methodology

- Estimating experimental value of $T_j - T_\infty$ and U_j
  - Calculate square error between the experimental mean temperature and the Response Surface Model for each possible subset of l locations within S_e^k as computed as

$$E = \sum_l \left\{ \Delta T_{m_e} - \Delta T_j \left[\beta_o(x,y) + \beta_1(x,y)\left(\frac{U_j}{U_\infty}\right) + \beta_2(x,y)\left(\frac{U_j}{U_\infty}\right)^2 \right] \right\}^2$$

    where $\Delta T_j = T_j - T_\infty$, $\Delta T_{m_e} = T_{m_e} - T_\infty$, and the sum is over l locations within S_e^k (the minimum number for l is 2)

    Example: Assume S_e^k contains six locations and let $l = 2$. For each possible set of two locations from S_e^k, the values of ΔT_j and U_j that minimize E are determined. This yields fifteen triplets $(\Delta T_j, U_j, E)$.

  - For a given value of l, the predicted values of ΔT_j and U_j, denoted by ΔT_j^l and U_j^l, are taken to be the triplet with the minimum E (*i.e.*, the values of ΔT_j and U_j with the smallest square error).
  - The procedure is repeated for all values of l from $l = 2$ to $n =$ size S_e^k.
  - The estimate for the experimental value of $T_j - T_\infty$ is the average of these values $T_j - T_\infty = (n-1)^{-1} \sum_{l=2}^{l=n} \Delta T_j^l$ and similarly for U_j.

Results

- Application of DDDAS Methodology

No.	*Step*	*Description*
1	1	A total of eighteen monitor locations were selected
2	2	Response Surface Models were generated at all monitor locations using $\Delta T_j = 66$ K
3	3	Six locations (Nos. 3, 9, 10, 14, 15 and 16) were selected for experiment
4	4	Using the experimental mean temperature measurements at the six locations, the estimated values $\Delta T_j = 110 \pm 16$ K and $U_j = 7.3 \pm 1$ m/s obtained using the RSMs
5	5	A new set of locations for experiments was defined based upon the RSMs (Nos. 2, 4, 5 and 17)
6	4	A revised estimate $\Delta T_j = 120 \pm 16$ K and $U_j = 7.1 \pm 1$ m/s obtained using the RSMs
7	2	A revised $T_j - T_\infty = 115$ K was selected for creation of the RSMs recognizing that the value originally used ($T_j - T_\infty = 66$ K) was far below the value predicted by the RSMs
8	4,5	The new RSMs yield the estimate $T_j - T_\infty = 105 \pm 13$ K and $U_j = 7.1 \pm 1$ m/s

- Result

Quantity	*Experiment*	*Predicted*
$T_j - T_\infty$	107 ± 10 K	105 ± 13 K
U_j	8.0 m/s	7.1 ± 1 m/s

Conclusions

- Developed DDDAS methodology for evaluation of fluid thermal systems
  - Examples are optical fibre furnace and turbofan combustor
  - Need for complete flowfield simulation to optimize system performance
  - Boundary conditions for flowfield simulation are not completely known *a priori*
  - Non-intrusive optical measurements (*e.g.*, laser diode absorbance) feasible in limited region
  - DDDAS method to determine complete boundary conditions by synergizing experiment and simulation
- Developed DDDAS method to determining T_j and U_j
- DDDAS method predicts $T_j - T_\infty$ and U_j within experimental uncertainty